Updates from the Detector Working Group

J. Estrada, A. Fava, Z. Gecse, V. Rusu

All-Scientist Quarterly Meeting
June 4, 2021

Introduction

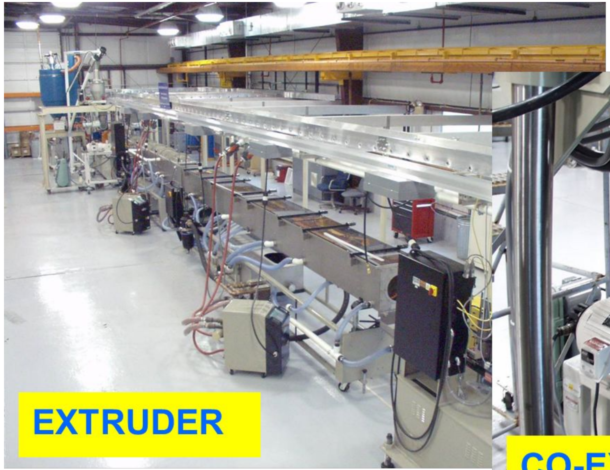
- Activities of the Detectors for Science working group slowed down since Snowmass process was paused. No meetings in 2021.
- Sensible progress in R&D in all frontiers, both on existing efforts and on new ideas.
  This is the main focus of this presentation.
- Support mainly from LDRD's, KA25 funds (New Initiatives) and some from Early Career Awards. Continuing this support, along with Laboratory commitment to invest in the future, is key for success!
- Most of these efforts are well integrated with the Snowmass process, i.e. submitted LoI
- Plan of the working group is to call for one big meeting of the detectors community in the Summer 2021, and start rebuilding momentum from there.

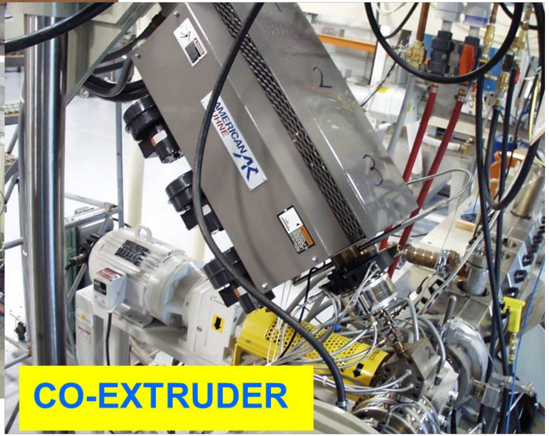
Energy frontier

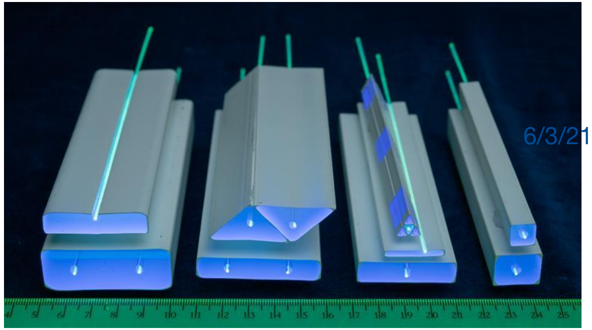
Fermilab one of world's largest producers of scintillator. Lab 5 extrusion past/present fabrication history

- FNAL experiments:
  - MINOS (supervision & QC)
  - MINERvA
  - Mu2e CRV – 2018
  - LDMX – 2021
  - CMS – 2021
  - EGP Egypt pyramids – 2021
- Large projects:
  - K2K (Supervision & QC)
  - T2K: P0D, ECal, INGRID
  - DoubleCHOOZ
  - Pierre Auger: CNEA
  - Pierre Auger: KIT 2015-21
  - ICECUBE
  - INO – CMVD - 2019
- Small projects:
  - CANFRANC – Spain
  - INFN: Bologna, Brescia, Gran Sasso, Napoli, Padova
  - Inst. Phys. Globe - France
  - NYU – Abu Dhabi
  - Tel Aviv University
  - UIS – Colombia
  - Univ. Liverpool
  - IDEON – Canada – 2021
  - Chichen Itza Tomography – 2021
  - SNOLAB –2021
  - NRL – 2021
- DOE complex:
  - ANL: STAR (Supervision & QC)
  - JLAB: CLAS, CDet
  - LANL

Fermilab extrusion facility NICADD at Lab 5

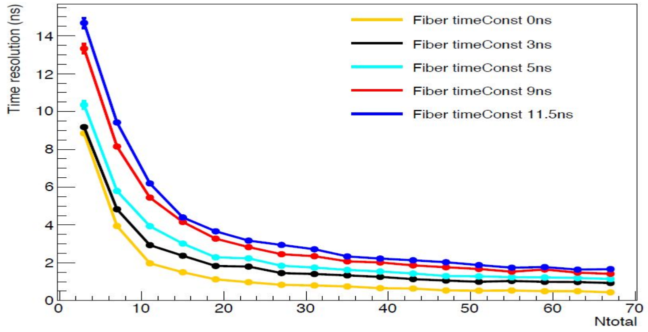






R&D to improve light yield and timing of extrusion/fiber/SIPM Application to MATHUSLA

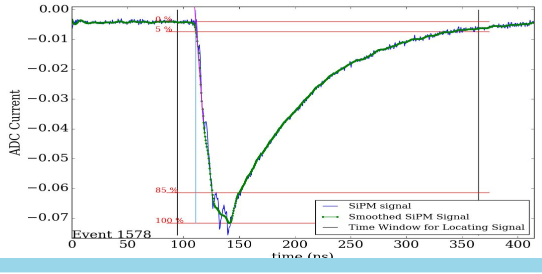
MATHUSLA baseline design extruded scintillator.
Needs 1000 metric tons of scintillator!!
Design requirement: <1ns timing measurement for position of particle along extrusion. (T1-T2)/2



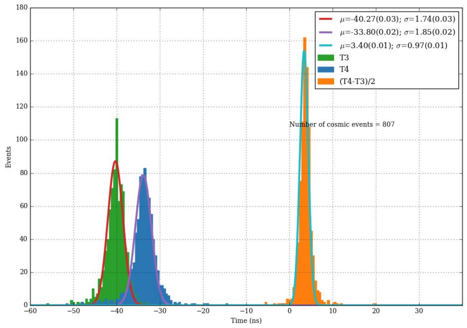
GEANT optics simulation of system.
Example: Vary WLS decay time constant.
Time resolution vs total light yield

Studies to understand factors for improvement of time resolution.

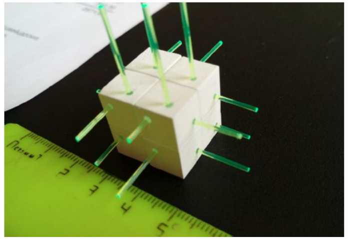
- Light yield
- WLS decay time constant
- Signal smoothing/shaping
- Edge determination/discrimination



Cosmic ray studies.
Have achieved <1ns rms on timing.



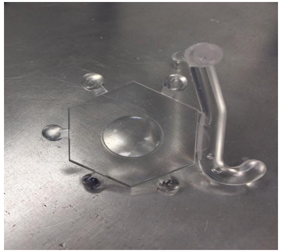
Injection Molding Scintillator for High Granularity Detectors



Voxel = 1.5X1.5X1.5 cm^3, 3 orthogonal holes for WLS fiber, white cladding

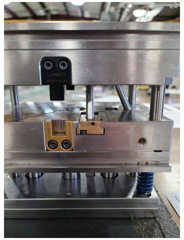
- Injection-molded scintillator is cost-effective way to make new generation fine grained detectors. (CMS HGC Scintillator section uses ~300K tiles; DUNE 3DST 3M tiles)
- **Capitalizes on FNAL expertise in scintillator**
- Concept is to build DUNE 3DST with injection molded tiles (voxels) where all voxel processing is done during injection molding: holes, opaque white coating. Goal is to develop a small scale prototype using in-house molded voxels
- Rate of progress increasing!

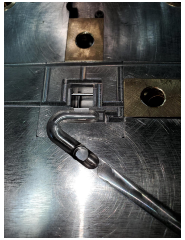
Injection molding machine at Lab 5 will be used to make the voxels.



First test pieces molded at Lab 5 April 2021

New Voxel mold ready to install at Lab 5





AC-LGADs

Collider Detector Tracking R&D

Overarching goals for future colliders (FCC, MuCol, …):

- Fast timing – aim toward 1-20 ps timing with
- Micron-level position resolution
- And several degree angular resolution
- Low mass and power

We address these goals using key new technologies:

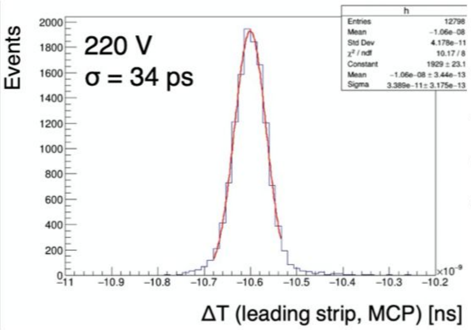
- Low gain avalanche diodes for improved s/n and low power
  - Buried layers for radiation hardness
- 3D integration to enable small pixels and low power
- Induced current signals in low capacitance systems
- AC coupling to provide position resolution
- System codesign of processing and readout to process fields of pixels
- Double sided processing for angular resolution

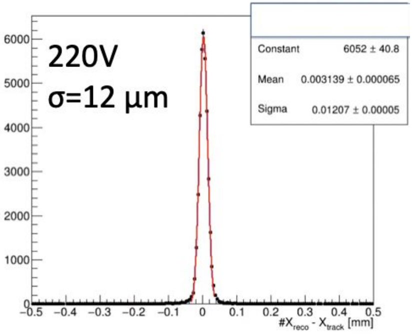
With collaborators

- BNL, UIC, UCSC, many others
- US Companies via SBIR

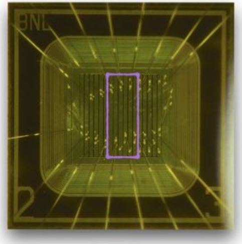
We need:

- Support for personnel and equipment at SiDet (now sadly lacking)
- Continued support for test and irradiation beams
- A strong ASIC group
- Contacts with foundries and industry
- Laboratory commitment to investment in the future





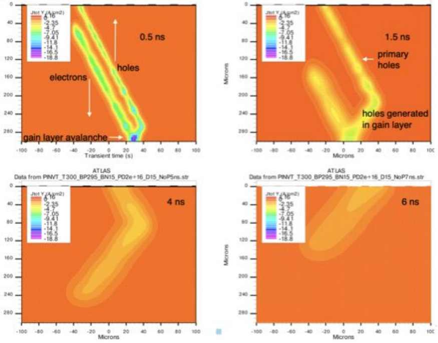
100 micron pitch, 20 micron



BNL strip AC-LGAD

World's first demonstration of sensor with simultaneous 30 ps and 5 µm resolution!

15 degree track detector internal current distributions



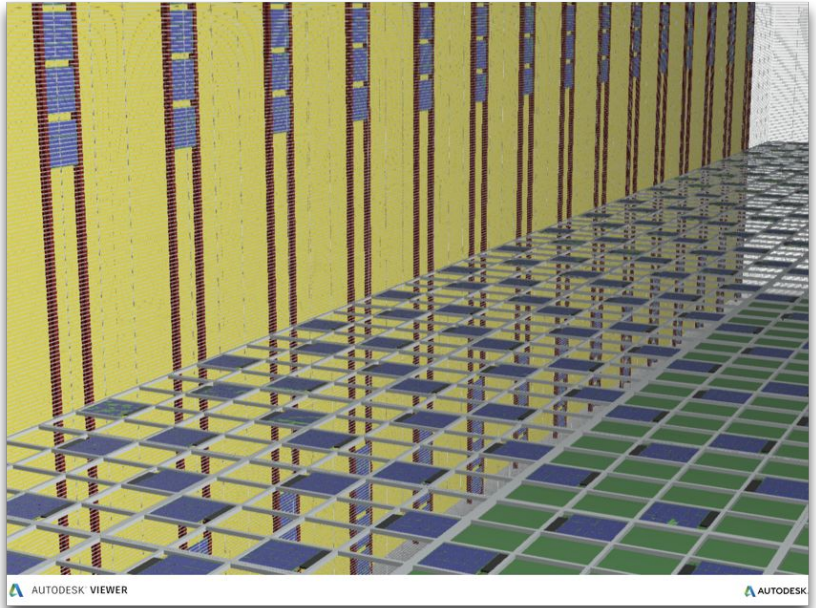
Simulation of double sided LGAD (small pixels at top)

Intensity frontier

Neutrino detectors

- In the near future, mainstream related to DUNE detectors:
  - pixelated detectors, cold readout electronics (ASICs), photodetectors for instrumenting high voltage surfaces for the Vertical Drift module, high pressure GAr-TPC, 3-dimensional scintillation tracker (3DST) for Near Detector (see Energy Frontier)
- Growing interest for reducing energy thresholds of LAr-TPC's both in terms of scintillation light and drift charge, for applications in neutrino physics (recovering missing energy, Supernovae neutrino, coherent neutrino scattering CEvNS) and dark matter
  - Studies of scintillation light properties, proportional scintillation and charge amplification in LAr, doping of LAr with methane+Xe and with photoionizing elements, infrared light in LAr, search for directional nuclear recoil in GAr-TPC equipped with GEM's, combined readout of light and charge with pixel detectors
- Effort for magnetizing LAr-TPC's
- Activities mostly carried out at PAB: upgrades of the facility (rehaul of cryogenic and electrical infrastructures, and creation of fully equipped workspaces for physicists to do project preparation, preliminary tests or proof of concept studies) and support of Neutrino Division engineers and technicians essential!

DUNE FD2-VD: photon detectors on the 300 kV cathode plane



View from inside the Upper Volume of the FD2-VD LArTPC
with PhDet-instrumented Cathode plane (xARAPUCA tile)

Require electrically floating

Photo-sensors and r/o Electronics

⇒ Power (IN) and Signal (OUT)

transmitted via non-conductive cables (i.e. optical fibers)

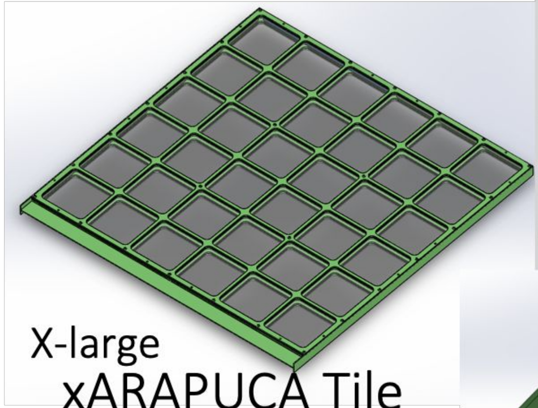
!! none of the commercially available technologies
(*PoF* and *Optolinks*) are rated to operate in Cold (LAr T)

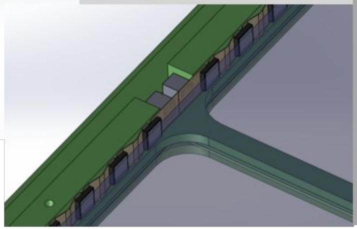
A highly specialized R&D - launched at FNAL (ND, SCD, AD, PPD *EE-dept.s*) in

collaboration with groups in US and International -

is currently ongoing

to develop *Cold custom Technology* for this application





X-large xARAPUCA Tile (new generation)

- 160 SiPMs (40 per side)
  - Glued to WLS Bar for improved optical contact
- SiPMs mounted on Kapton flexi-PCB
  - Addresses relative thermal contraction of elements
- Power-to-Glass FB-118 HQE WLS plate (Milano)

PoF - Power over Fiber

■ Proprietary and patented silicon based Vertical Multi-Junction (VMJ)

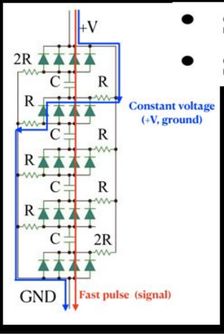
Relatively new technology rapidly developing used for systems requiring isolation – eg. PhotoVoltaic Cell Towers, and Low Noise Experimental Systems

FD2-VD PhDet: Lasers Transmitter+Fiber → *Low Volt/High Current* Receiver (CE)

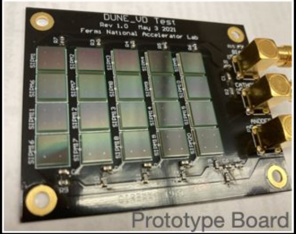
→ *High Volt/Low Current* Receiver SiPM

- HV/LC - PoF: COTS Si-based Receivers fully validated in cold
- LV/HC PoF: high efficiency GaAs-based Receivers better suited for low temperatures
  - Custom units with building voltage specification under development

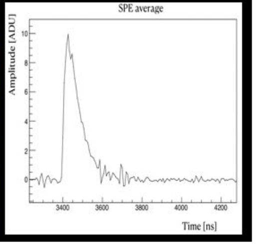
Largest SiPM array → One Channel (new solution):
20 ***hybrid*** Passive ganging X 8 ***OpAmp*** Active ganging



- Small capacitance → short recovery time
- Same bias voltage of a single SiPM



Prototype Board



SoF - Signal over Fiber

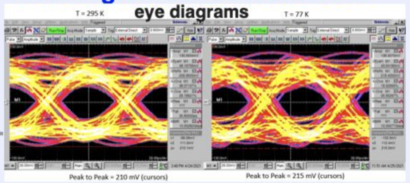
Test Program at 295 K and 77 K

Validation in Cold

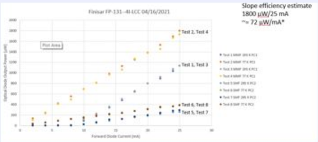
Selection

Laser Driver → *Driver Testing*

Binary "1"
Binary "0"



Laser Diode → *Diode Testing*

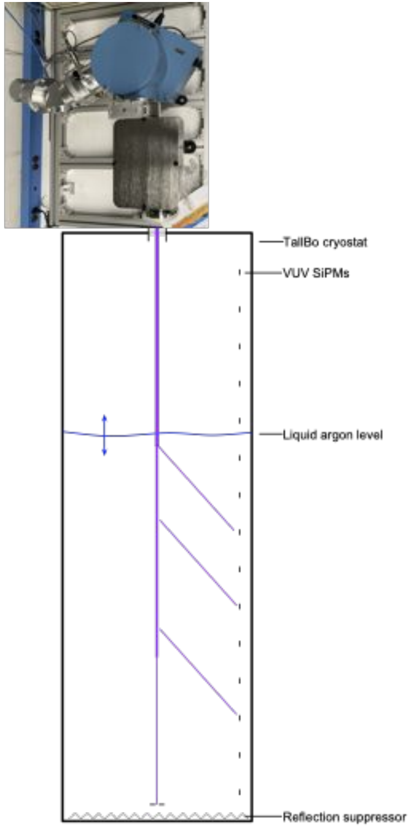


COTS Transceivers

FD2-VD PhDet:

Fermilab

Studies of scintillation light properties



- Not R&D – supporting measurement for LAr Photon Detection.
  - But, make use of Detector R&D facilities and equipment at PAB.
- Preparing measurement of attenuation and scattering in LAr vs. wavelength using a monochromator.
  - May follow-up with a measurement of material reflectance.
- Receiving strong support from PAB technicians and engineers.

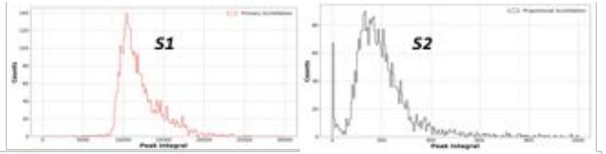
A. Himmel _ ECA 2017

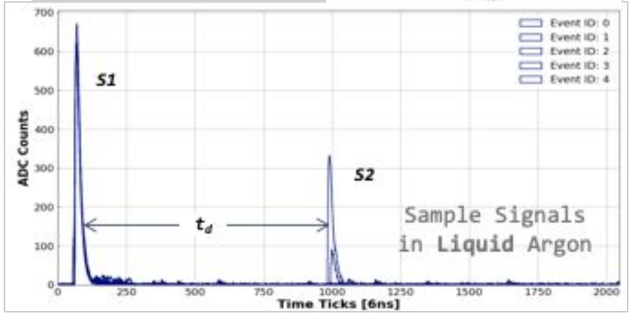
Proportional scintillation light in LAr

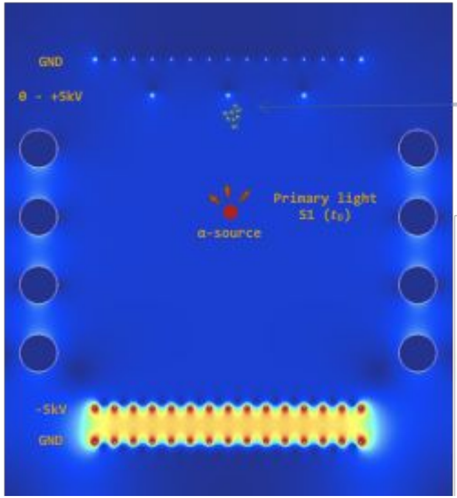
- **Goal**
  - Measure the proportional light in **Liquid** argon
- **Challenge**
  - Create high field above the threshold for the proportional light
- **Method**
  - Use the strong field (**~MV/cm**) around the thin wire (**12.5um**) to produce the proportional light

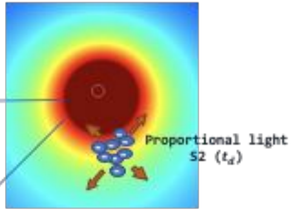
✓ **Status**
  - ✓ First cryogenic run shows very promising

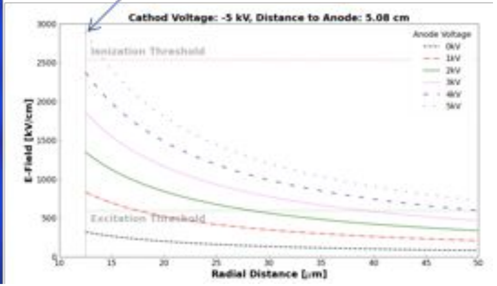
➢ **Plan**
  - ➢ Scan anode voltages from **0 to 5kV**
  - ➢ Understand the **threshold** and **gain** for the proportional light





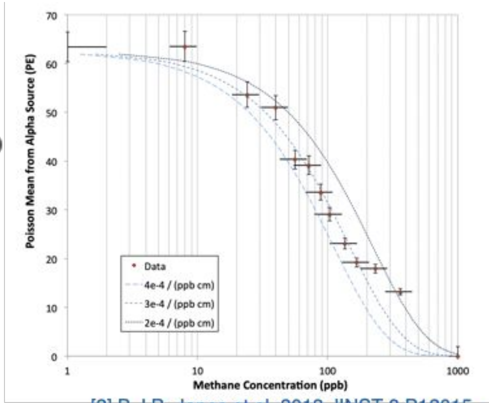






Introduction of Free Protons into LAr Detectors via Xe+CH_4 Doping

- Two main physics motivations
  - Sensitivity to low-energy anti-electron neutrinos via inverse beta-decay
    - Additional channel to detect supernova burst neutrinos and diffuse supernova neutrino background (DSNB)
    - Anti-electron neutrino appearance at pion decay-at-rest neutrino sources
  - Neutron tagging via neutron capture on Hydrogen
    - Improved modeling and reconstruction of high-energy neutrino-Ar interactions
    - Background rejection in rare searches, e.g. proton decay, coherent-elastic ν-nucleus scattering (CEvNS), DSNB
- LAr doped with high concentrations of Methane (CH_4) works well as a TPC [1], although the LAr scintillation light was shown to be strongly absorbed [2]
- LAr doped with Xe shifts scintillation wavelength away from strong CH_4 absorption region
- Project goal is an unambiguous demonstration of the ability to detect scintillation light after Xe+CH_4 doping
- Effort largely uses readily available equipment at PAB through Neutrino Division
  - Engineering/technical support provided from Neutrino Division
  - TallBo LAr cryostat



[2] B.J.P. Jones et al. 2013 JINST 8 P12015

Gas injection system at PAB

[1] E. Aprile et al. NIM A253 (1987) 273-277

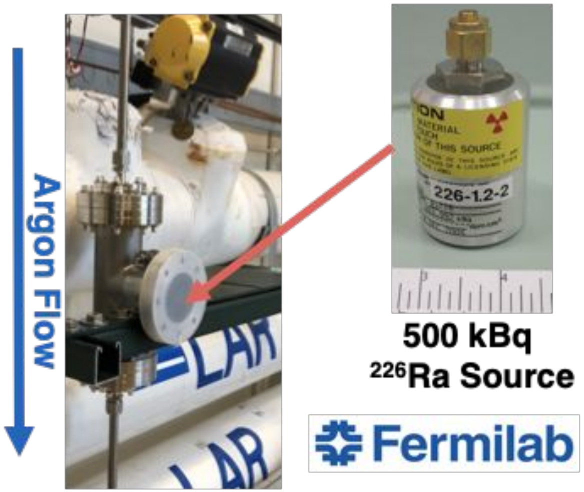
LAr-TPCs for MeV scale Physics

- **Goal:** Use radioactive sources to measure LArTPC MeV-scale performance and explore improvements through addition of photosensitive dopants

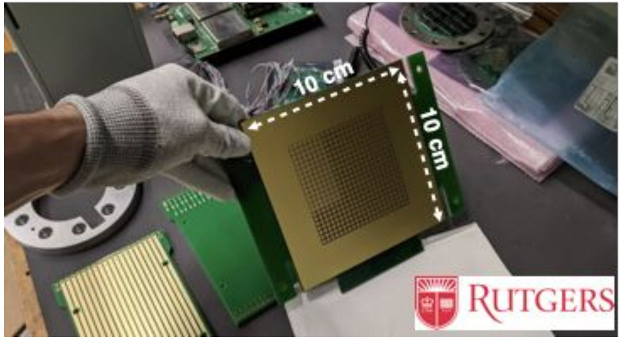
- **@MicroBooNE:** Add radon source to study MeV-scale energy resolution
  - **Status:** Source holder installed and will add source soon, data analysis will begin immediately

- **@PAB:** Deploy a pixelated LArTPC to study gamma-sources into the Blanche cryostat with photosensitive dopants
  - **Status:** All components delivered to Rutgers from LBNL & CalTech, assembly will begin soon

Radon doping MicroBooNE



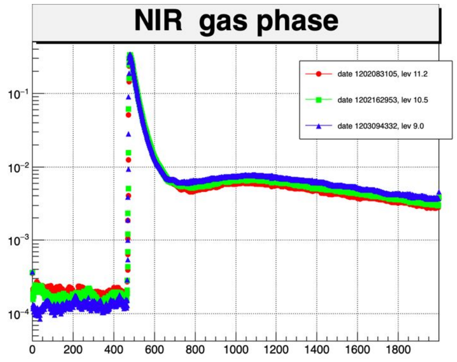
Assembling 3x3 tile TPC



F. Psihas, J. Zennamo (FNAL), I. Lepetic, A. Mastbaum (Rutgers)
KA25 New Initiatives 2020 and Neutrino Division

Near Infrared in liquid argon

Ran a preliminary experiment in the cryostat TallBo at the Proton Assembly Building (PAB).
Simple setup: One NIR and one VUV SiPM "looking" into an Am241 source.

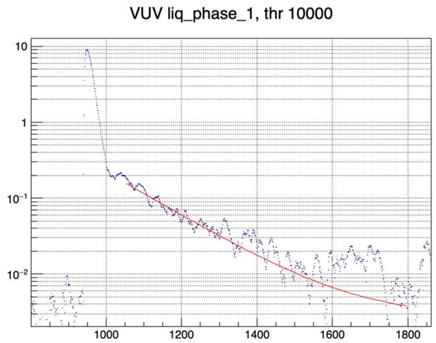


Support needed for a NIR detector that could reach beyond 900 nm

Candidate detectors: InGaAs SPADs from Princeton Light Waves in the US and MPD in Italy

Took data in both LAr and GAr with different contents of N_2 contamination
Puzzling slow component in the gas phase seen by the NIR SiPM at 3 μs (horizontal axis: 1 SSP tick is 6.7 ns)

Also for the VUV we find a puzzling two slow components at τ ~ 300 ns and τ ~ 1170 ns.
NB: we do not use WLS.



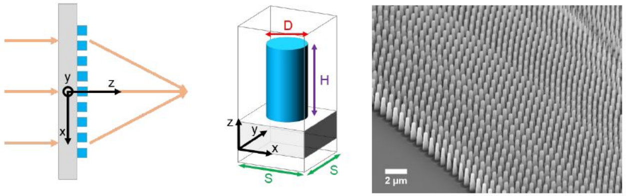
C. Escobar, A. Para, P. Rubinov

Fermilab

Metalenses as light concentrator in noble element detecors

Develop metalenses, flat optical elements fabricated with nanotechnology, suitable for use as light concentrators in noble element detectors, gaseous or liquid.
Concentrate scintillation light into SiPMs.

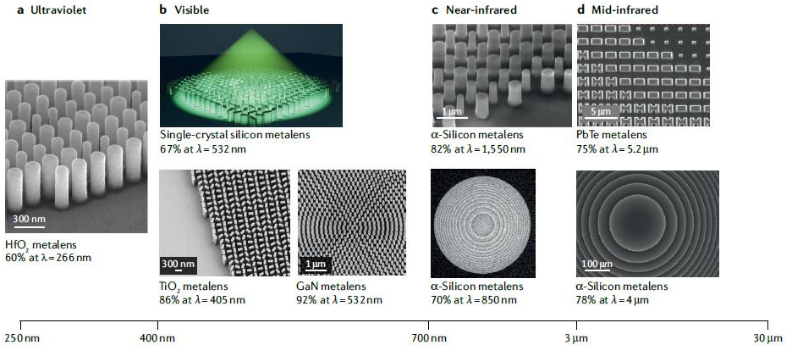
Many challenges: index of refraction mismatch between detector media and substrates; sub-wavelength fabrication scale < (λ/2NA)   NA… numerical aperture (needs to go below 100 nm); wide range of angles of incidence: defeating the etendue limit!
Currently characterizing existing metalenses optimized for visible wavelengths and designing metalenses for shorter wavelengths nearing the UV.



(a) Schematic representation of a metalens nanostructures.

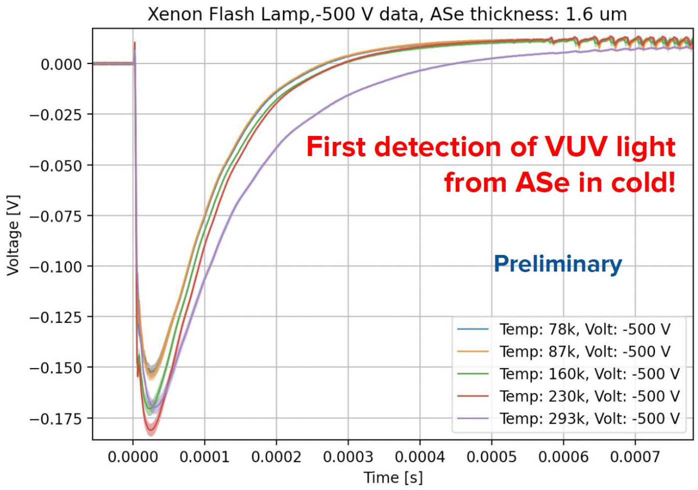
(b) SEM image of our metalens nanostructures.

From: Chen, Zhu and Capasso: *Nature Reviews Materials* **volume 5**, pages 604–620(2020)



C. Escobar, A. Para, M. Stancari with Harvard groups of R. Guenette and F. Campasso
LDRD + additional support needed for accessing EUV lithography (SUNY Albany/IBM)

LILAr: light imaging with liquid argon



Long term goal: Develop multiple modality pixels capable of reading VUV scintillation light and femtoCoulmb charge:
harvest the benefits of pixelated TPC and powerful light collection system.

Short term goal: The light side. Detection of scintillation light in liquid noble elements on wide surfaces using thin films of amorphous semiconductors and dopant cocktails for both visible and VUV light at cryogenic temperatures.

Status:

⟶ In collaboration with UTA theorists: Developed a first simulation based on density functional theory for optical properties.
1st paper on the archive: 2104.14455

⟶ Test from 293 - 77K with VUV light on first prototypes (at ORNL): **we saw signal!**

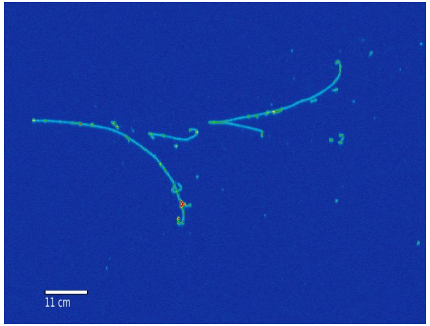
⟶ 3rd prototype: 25 micron pitch on its way (achieve higher field)

⟶ Ar purity test on its way

Lab Support:

⟶ Availability of technicians and time at machine shops is fundamental for small “high-risk high-reward” R&D projects. By nature, this work is seldom programmatic, but it is often limited in time. We need more flexibility in the resources we have and more resources in general if we want to keep small R&D alive and competitive with Universities.

Magnetised LAr-TPC

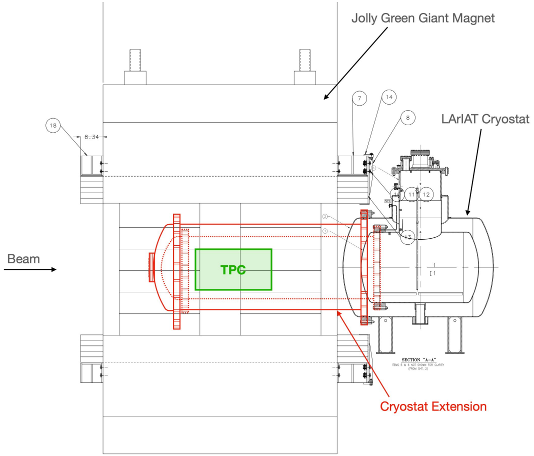


Simulation of magnetized LArTPC

There is a wide interest in **magnetizing LArTPC detectors** for neutrino physics and beyond. The magnetization would allow us to determine the **electric charge** of particles (information not available in non-magnetized LArTPCs), and it would provide an additional method to **measure the momentum** of particles.

Proposed milestones: (i) magnetize the **LArIAT detector** using classical magnet; (ii) magnetize **SBND** with superconductors inside the cryostat; (iii) magnetize the 4th **DUNE** module.

Jolly Green Giant Magnet at Fermilab



Proposed modification to LArIAT for using it inside the magnet

Lab support needed for test beam and magnet operation, fabricating the extension to the LArIAT cryostat, setting up LArIAt at FTBF and data taking.

M. Del Tutto, O. Palamara, C. Montanari, R. Acciarri, F. Cavanna, W. Badgett, A. Fava

Cosmic frontier

New Materials for Dark Matter Direct Detection

- keV-MeV dark matter detection requires meV thresholds for particle-like dark matter, also opens windows into absorption of meV-scale bosonic DM
  - Requires exploring low-gap materials
  - Requires development of more sensitive readout electronics

- Technology Development Directions
  - Improving the Sensitivity of Athermal Phonon Sensors for Light Mass Dark Matter - *LBNL Lead*
  - Cryogenic Carbon Detectors for Dark Matter Searches - *FNAL Lead*
  - Low-gap charge detection for fundamental physics searches - *FNAL Lead*

- Understanding Material Response
  - Sub GeV DM-Nucleon Scattering via Collective Excitations: The Inelastic Regime - FNAL/UChicago Lead
  - Coupling Experiment and Simulation to Model Non-Equilibrium Quasiparticle Dynamics in Superconductors - FNAL Lead

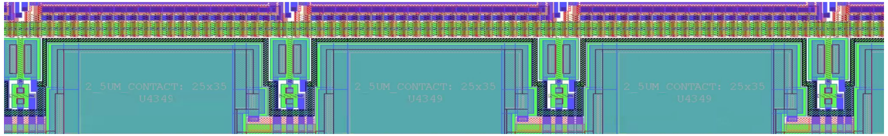
- Kurinsky coordinating CF-1 Low-Threshold Landscape white paper, will integrate these ideas to ensure they are prominently featured

Silicon detectors with non destructive readout

Non destructive readout has demonstrated to be a very powerful tool for single charge and single photon detection. This sensor has been used for many applications: quantum imaging, dark matter searches, neutrino detection, new astronomical instruments, etc.

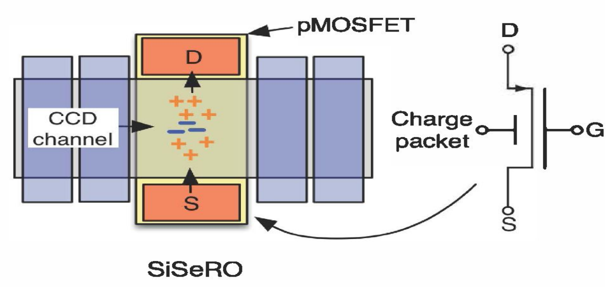
Lines of work:

- Speed up current versions of non destructive readout.
  - Multiple output stages.
  - Multiple-amplifier output stage.



Designed by Microsystems Laboratory at LBNL

- Improvements in the gain of the output stage.
  - SiSero amplifier.
  - CMOS fabrication processes. Smaller structures.
- Noise reduction techniques:
  - Smart readout capability.
  - New fabrication processes.
  - On-chip or on-package active electronics.



https://doi.org/10.1117/1.JATIS.5.2.021015

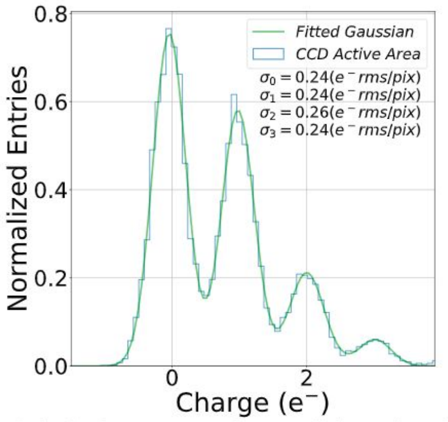
Axion Direct Detection Experiments

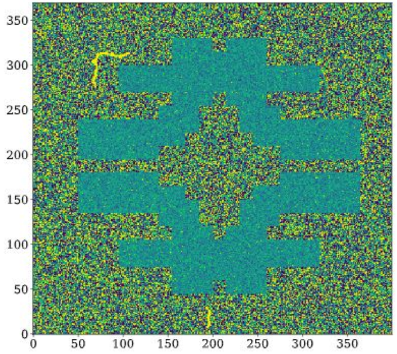
- Fermilab scientists were active in preparation of many Snowmass LOIs related to future axion searches:
  - Extension of ADMX to 2-4 GHz (Dak Matter New Initiatives Project)
  - Axion haloscopes from 4-10 GHz
  - Axion detection beyond the quantum limit
  - Frequency multiplexed axion dark matter searches
  - ADMX high resolution search
  - Broadband high frequency detectors
  - US participation in MADMAX
  - Qubit-based detectors
  - UP-conversion Loop Oscillator Axion Detector
  - High field magnets for next generation searches
  - Non-equilibrium quasiparticle dynamics in superconductors

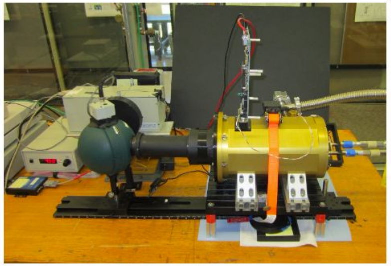
- Now starting up work on two white papers:
  - Resonant cavity experiments. Expected to be comprehensive summary of US and international efforts.
  - "Discovering GHz-THz axion dark matter" to be led by Fermilab postdoc Stefan Knirck will capture ideas for axion discovery with broadband detectors.

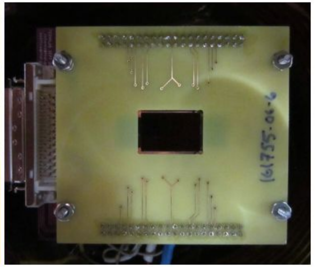
Skipper CCDs for Cosmic Surveys

- Reducing noise to ~0.5e- rms/pix can lead to a ~50% increase in survey speed for some applications
- Selecting regions of the detector can further improve survey speed and efficiency
- Target a future spectroscopic survey (there are ~4 facility concepts being proposed to Snowmass)









R&D for CMB instruments

Topic	Primary	Secondary
CMB Spectral Distortions: A new window to fundamental physics	Jens Chulba, Suvodip Mukherjee	**++, Benson**
CMB-HD: An Ultra-Deep, High-Resolution Millimeter-Wave Survey Over Half the Sky	Neelima Sehgal	**++, Benson**
Primordial Non-Gaussianity with Millimeter-Wave Line Intensity Mapping	**Kirit Karkare**	**++, Anderson, Benson, Simon**
Millimeter-Wave Line Intensity Mapping Facilities	**Kirit Karkare**	**++, Anderson, Benson, Simon**
Cosmology with Millimeter-Wave Line Intensity Mapping	**Kirit Karkare**	**++, Anderson, Benson, Simon**

Instrumentation for Future Cosmic Surveys

Write a white paper that brings together roughly a dozen cosmic survey instrumentation LOIs:

- **Detector technology:** fully depleted CCDs, skipper CCDs, germanium CCDs, non-destructive CMOS, MKIDS
- **"Photon Systems":** fiber positioners, photonics, ultra-high-resolution interferometers, multi-photon interferometers
- **Development and Testing Facilities:** detector fabrication facilities, calibration facilities, astronomical testing facilities

Fermilab involvement: Cancelo, Diehl, Drlica-Wagner, Estrada, Kurinsky, Moroni, Sofo-Haro, Tiffenberg, and many more

Developing Small-Pitch Optical Fiber Positioners for Massively Parallel Spectroscopy

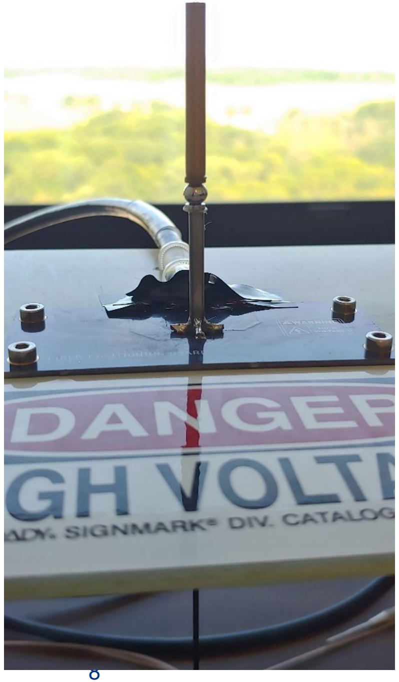
DES/LSST will need new telescopes and instruments to attain sufficient amounts of spectroscopic follow-up.

A limitation on the number of spectra that can be simultaneously acquired is the size of the Fiber Positioner. Currently used technologies permit ~ 1 cm distance between them.

Our LDRD Goal is to build 5 to 6 mm pitch optical fiber positions for massively parallel spectroscopy.

Authors: H. Thomas Diehl (Fermilab), Marcelle Soares-Santos (U. of Michigan), Michael Schubnell (U. of Michigan), Anushka Shrivastava (U. of Michigan), Curtis Weaverdyck (U. of Michigan), Jennifer Marshall (Texas A&M U.), Kyler Kuehn (Australian Astronomical Observatory -- Macquarie U. & Lowell Observatory), Jon Lawrence (Australian Astronomical Observatory -- Macquarie U.), Alex Drlica-Wagner (Fermilab), Terri Shaw (Fermilab), Steve Kent (Fermilab), Parth Ghandi (Fermilab)

Prototype Tilting Spine @ FNAL



Precision frontier

Precision frontier R&D challenges

- Radiation hard electronics
  - Component qualifications is needed
- Fast rad hard calorimeter
  - <10% energy resolution and 500ps timing
  - ~1MRad and 10^{13}n_1MeV/cm^2
- Ultra low mass tracker
  - <0.1% X_0 with <100ps TOF tracking for PID
- High efficiency cosmic ray veto system
  - >99.99% efficiency, neutron fluency issue on SiPM/scintillator
- High power, rad hard POL delivery
  - Radiation and B-field hard DC/DC converters
- Sub-ns electronics/trigger
- Series of workshops on mu2e-II

mu2e-II tracker - R&D towards low mass tracker

- 8 micron wall thickness, spirally wound, Mylar straws → tested for mechanical properties
- Thin straws, new handling and construction techniques will be tested → constructing a small 8 straw prototype panel which may then be further tested.
- Test stand to test permeation and resistance of mylar with different amounts and types of metal deposit.
- Simulations in parallel to understand different geometries

mu2e-II calorimeter

- BaF_2 → excellent candidate for a fast, high rate, rad hard crystal for calorimetry
- R&D on SiPM for readout
- Other possible techniques include different crystals (LYSO), nanoparticle wavelength shifters, LAAPDs, etc.